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FORCE SYSTEM FROM STRAIGHT ARCHWIRES

IN VARYING TWO BRACKET-GEOMETRIES----AN EXPERIMENTAL STUDY

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B.D.S., National Defense Medical Center, Taiwan, 1982

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IN VARYING TWO BRACKET- GEOMETRIES ---- AN EXPERIMENTAL STUDY

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I dedicate this thesis to my wife, Yuan-Yuan, without her understanding and support , this study will not be completed.

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INTRODUCTION

Since the straight wire appliance concept was introduced in the early 70's (Andrews, 1970), the trend of using pre-adjusted angulated and torqued attachments and straight archwires in the orthodontic treatment increased tremendously. Following the invention of the new alloys such as the Nitinol, Beta-titanium, Nickel-titanium wires and braided wires, it is now possible to eliminate the wire loops and use a plain archwire for initial aligning the malposition teeth because of the low stiffness of these modern wires. Burstone (1981) proposed the variable-modulus concept that forces magnitude could be controlled by varying primarily the material other than the cross section of the wire. Now, it is more convenient and possible to have a true straight plain archwire to deliver an optimal force for tooth movement. Nevertheless, an optimal force delivery does not necessarily mean the tooth will move to a right direction and the force system between the archwire and the attachment is still obscure. Most clinicians determine the force system by reading the archwire and they tend to believe the "Ideal Arch Principle" , which states that if a wire is bent into the shape in which one would like the attachments to be found out after the treatment, the teeth will move to that position. This is somewhat true if one considers a very rigid wire that acts as a mold and the teeth are moved slowly by intermittent ligation in a short distance. Yet, most orthodontists use highly flexible wires in the initial stage of treatment, and as the flexibility increases, a more complicated force system exists and commonly causes the undesirable side effects.

The complicated force system of the attachments along the archwire can be evaluated more clearly by using a two-tooth model and later summing a series of models to give a complete picture. Computer-simulation models were used to calculate the force systems in an ideal arch (Burstone and Koenig, 1974). It was found that the force systems were determined by the geometry between the attachments and the archwire. Wire-attachment geometry is defined by the interbracket axis and the angles of the brackets between the archwire. The force and moment values in different class geometry can be calculated and so the type of tooth movement can be predicted. However, this theoretical model is based on the small deflection linear beam theory of the wire and the result may not be accurate. Recently, a theoretical model based on the large deflection theory and under different boundary conditions was used to calculate the force systems (Koenig and Burstone,1989). Large mesio-distal forces (horizontal force) were found if the wire is not allowed to slide freely and so frictional force plays a significant role in the force system.

Frictional force becomes important in orthodontic practice because of the common use of sliding mechanics to close a space between two tooth segments along a plain archwire. Frictional force generated when the wire slides through the surface of the attachments. The value of the force can be calculated from the normal force perpendicular to the surface and the coefficient of friction of the materials in contact (Coulomb's Law) (Palmer, 1957).

The purpose of our study is to develop a laboratory experimental two-tooth model to measure the moments generated between the attachments and a straight archwire in different classes of attachment-wire geometry. The previous studies were done with computer stimulation and no actual measurement is ever made. The influence of the following factors is evaluated: 1. wire-attachment geometry 2. interbracket distance 3. wire material 4. wire size 5. bracket width and 6. deflection of the wire.

Force System

If a force is applied to a tooth and does not pass through the center of resistance, a moment will be produced. The moment is a vector which has direction and magnitude. Its magnitude equals to the force magnitude times the perpendicular distance between the line of action and the center of resistance of a tooth. Its direction is determined by the direction of the force. The moment of a force about a specified point of line is also a measure of the potential of that force to rotate the body. (Nikolai, 1985). Different type of tooth movements can be characterized by the location of the center of rotation that is depended on the ratio between the moment and the force applied to a tooth (M/F ratio) and not on the absolute values. The center of rotation may be varied from a point of infinity (translational movement) to a point of the incisal edge (root movement) (Burstone '85). Therefore, by knowing the exact moment to force ratio applied to a tooth, orthodontists can move a tooth to the right position and minimize the side effects. However, most clinicians tend to figure out the force system by reading from a wire or may even use a force gauge to measure the magnitude directly inside the mouth. In most circumstances, this cannot give a correct answer because the force system involves so many variables and is statistically indeterminate.

Drenker (1988) used a three-moment equation to show that when only one single tooth was displaced from the ideal position, every part of the wire was elastically involved in distributing the reactive forces resulting from the deflection at that one slightly displaced tooth.

A theoretical model using computer simulation was built up to calculate more accurate quantitative data of the force system involved in a straight archwire and the malpositioned teeth (Burstone and Koenig '74). Two-tooth model was used because of its simplicity and the complicated force system of the whole arch can be determined by summing the serial results. The theoretical model was used to study the force system in one plane of space, and used a 0.016 inch high-temper stainless steel straight archwire (400,000 p.s.i. yield strength) placed between malposited teeth. The wire-attachment geometry is defined by the angles of the brackets between the interbracket axis (Fig. 1). The following sign convention is used for forces and moments. Anterior force; lateral force; mesial force ; buccal force and extrusive force are positive. Posterior force; medial force; distal force; lingual force and intrusive force are negative. Moments tending to produce mesial; labial or buccal crown movement are positive (+), and moments tending to produce a distal or lingual crown moment are negative (-). As an action of a force must have a reaction (Newton's third law of Statics), the force system in the wire is the opposite of the tooth.

In Class I geometry, the two angles between the wire and the attachments are the same. Two equal and positive moments would act at each tooth position (position A and B). Although the magnitudes of the moments may vary, depending upon the amount of activation and the interbracket distance, the ratio of M_A to M_B always remains +1. Besides the moments, two vertical forces are also produced at the teeth. Force A equals to force B at equilibrium. The Class II geometry is characterized by θ_A having a magnitude of one half of θ_B. Two positive moments are created at the wire at position A and B. The magnitude of the moment at A is 0.8 of the moment at B. A positive force is found at A, and a negative force at B. In Class III geometry, the interbracket axis cuts across the two brackets, so that the ratio of θ_A to θ_B is zero. The moment at position A is one half the moment at position B. In addition, vertical forces are produced on the wire- positive at position A and negative at position B. In geometry IV, the ratio between the angles is -0.5. In this geometry, a positive moment is found at position B, but no moment at position A. In geometry V, the ratio of θ_A/θ_B is -0.75. In this case, the moment at A is negative and its magnitude is two fifths of the positive moment at B. In geometry VI, the angles between the interbracket axis are the same but in opposite direction ($\theta_A/\theta_B = -1$). The force system acting on the wire is composed of equal and opposite moments (negative at A and positive at B). The moment-to-force ratio is constant for any given class and interbracket distance, regardless of the amount of deflection. However, the M/F ratio increased proportionately with the interbracket distance. The vertical forces at position A and B were equal in each case, but their relative magnitudes decreased as the ratio of θ_A/θ_B became smaller.

Nevertheless, the above results and the studies by DeFranco (1976), were based on small deflection theory and confined to non-rotated geometries and rigid attachments. The small deflection theory was accurate to provide the data for qualitative evaluation of the appliance. The quantitative aspects of the simulations were less accurate, since most of the flexible wires undergo large activation in the clinical use. Also, in rigid boundary condition, the wires and the brackets are not allowed to slide or rotate during activation. A more advanced analysis was used to overcome the above limitations (Koenig and Burstone ,89). The model produced simulation that calculated more accurate quantitative results compatible to clinical situations. The analysis based on large deflection considerations, simulated activation in three planes of space that were large and were affected by the manner in which the bracket interacts with the wire. The effects of bracket-wire sliding with rotated boundary condition are also available. The force systems from an ideal arch were reevaluated with the large deflection considerations. Compared to the previous study with small deflection model but under non-rigid boundary condition, the large deflection model produced similar result in Class I geometry. The ratio M_A/M_B was 1 and only small amount of horizontal force was produced. However, under rigid boundary condition that the archwire was not allowed to slide through the bracket, a slight increase occurred in the magnitude of moment M_A and M_B and enormous amount of horizontal force was found. The actual force system was depended upon how much that wire slid. The result in this paper showed that if the wire is not restrained, the previously established M_A/M_B ratios hold true. However, if the wire is restrained, the ratio between the moments might deviate significantly from the unrestrained situations.

If the activation of a wire is increased beyond a given point, permanent deformation will begin to occur. When this point is reached, the appliance will not deliver any more force without permanent deformation. This point defines both the maximum force and the maximum deflection or activation of a wire in the elastic range. The load-deflection rate defines the stiffness or rigidity of the wire and is the slope of the force-deflection curve. The stiffness of an orthodontic wire is dependent not only on its material properties but also the cross section. Modulus of elasticity and the moment of inertia (EI) are the parameters that determine the load-deflection rate of the wire and, along with other configuration parameters, determine the overall load-deflection rate of the appliance. The maximum force is partly configuration-dependent and changes with the span length. However, the maximum bending moment is a constant for any given orthodontic wire dependent only on the material properties of the wire and its cross section (Burstone and Goldberg, 1983). The wire will permanently deform once the maximum bending moment is reached.

When a beam such as an archwire is loaded in flexure, the moment produced at any cross-sectional plane along the wire equals the force times the distance from the plane to the point of load application. For two arbitrary wire composition/beam configuration (x and y), the relative stiffness ratio is equal to $(EI)_y/(EI)_x$; E = tensile(Young's) modulus. For a round wire, $I=d^4/64$; therefore the stiffness ratio between two different round wires is equal to $(Ed^4)_x/(Ed^4)_y$. (Kusy and Greenberg 1981).

Horizontal Restraining Forces

Whenever a wire slides through the bracket, it experiences a resistant force. The resistance that precludes actual motion is termed static friction and that exists during motion is called kinetic friction. The classical laws established by three French physicists of the 17th, 18th and 19th centuries- Guillaume Amontons, Charles A. Coulomb and A. Morin may be summed up in four brief statements. 1) The frictional force, f is directly proportional to the load W (normal force); 2) the frictional force depends on the nature of the sliding surfaces; 3) it is independent of the area of contact between the surfaces and 4) It is also independent of the sliding velocity. The ratio, f/W is called the coefficient of friction for a given pair of sliding surfaces (Palmer 1957)

Modern friction theory is based on the premise that solid surfaces are in contact only at a few minute points or asperities. It is the shearing of the real contact area that causes a tangential resistive force or friction. The adhesion theory of friction assumes that, at asperity contact, the stress is concentrated and plastic deformation occurs, bringing minute area into close enough contact for interatomic force to act. Adhesion occurs at these points and friction involves breaking of the junctions or shearing of the weaker material in the junction. Then, the real area of contact is inversely proportional to the hardness of the softer material and proportional to the load. It indicates that there are two material properties involved in determining the frictional force for a sliding couple, shearing strength and something involving compressive yield strength and hardness. Factors that influence friction includes temperature, surface film, surface hardness, lubrication, surface roughness, crystal structure, load and sliding speed. To a deeper understanding, friction is a surface state (adsorbed molecules, roughness, surface work hardening, state of oxidation, temperature and lubrication). Except in the condition of clean surfaces in high vacuum, the friction of two sliding surfaces is not a function of the specific materials, but, of the surface state at the sliding interface (Glaeser 1970).

Moving a tooth along an archwire allowed orthodontists to have better control of the spatial relation of the adjacent tooth segments, but they would face a difficult problem, friction, to encounter. Most previous orthodontic studies involved friction concerned about the resistance during simulated canine retraction along an archwire. As the retraction force does not pass through the center of resistance of a tooth, the tooth movement pattern consists of multiple steps of tipping and uprighting of the tooth. The factors that influence the magnitude of frictional force may be subdivided into those affect the magnitude of the normal forces and the coefficient of friction.

Increase tipping of a tooth relative to adjacent teeth increases the force necessary to overcome friction. Increased wire size , particularly the occlusogingival dimension increases the frictional force (Andreasen 1970). Friction is partly a function of the moments acting at bracket-wire interface (Thurow '72). Those moments are not only dependent on the bracket angulation, but on a complex interaction of factors related to wire stiffness (Young's modulus and Moment of inertia) and appliance design stiffness (bracket width, interbracket distances and boundary). For small angulations, in which second-order bracket/wire binding was absent, ligature tie force was a highly influential independent parameter. Rectangular wire generated more friction than round wires, and wire materials ranked according to their surface roughness. When angulation was large and binding between wire and bracket was substantial, wire stiffness in bending, which depended on wire cross-sectional size and shape, wire material and interbracket distances, was apparently influential in determining friction resistance as was the contact area between wire and bracket slot. Variations in interbracket distances, to the extend generally encountered in canine retraction, did not substantially influence frictional resistance (Frank, 1980). Drescher' study (1989) found the following factors in decreasing order to affect friction in tooth-guided archwire mechanics : retarding force (biologic resistance), surface roughness of wire, wire size (vertical dimension), bracket width, and elastic properties of wire. In general, an increase in wire size was associated with increased bracket-wire friction (Kapila ,1990). Most of the findings from the above studies were concordance with others. However, the most controversial factor affecting friction is the bracket width. Andreasen's study found that three bracket widths (0.018", 0.135".0.1") were somewhat independent of the force to overcome friction. Frank, Tidy and Kapila's studies indicated that wider brackets could generate higher frictional resistance during translational movement of the bracket along an archwire in vitro. However, a study at the University of Connecticut (Feeney ,1988) used a model of binding moment to prove that frictional force is inversely proportional to the bracket width. The study by Drescher also found the similar result. The conflict is mainly due to the degree of freedom given to the simulated tooth in these setup as compared with the spatially restrained tooth movement designed in previous studies. Also the component of the normal force caused by the increased ligation force in the wider bracket in Kapila's experiment also may contribute to the diversity.

The coefficient of friction is affected by the different metal surfaces in contact due to surface roughness. TMA wire is exceptional and create more frictional force when compared to nitinol and stainless steel because substantial cold welding occurs between the beta-titanium wire and the stainless stain bracket.(Peterson and Spencer 1982, Garner 1986, Drescher 1989, Tidy 1989 and Kusy 1990). However, in Prososki's study (1991), no significant correlation was found between arithmetic average roughness and frictional force value of different brands of nickel-titanium archwires. It was mentioned that with intermediate ranges of surface roughness, the frictional forces are independent of surface roughness. Generally , a ceramic bracket increase the frictional coefficient of different bracket-wire combination. It generates more frictional force with the beta-titanium wire as the ceramic brackets have significant abrasive effect on this soft wire (Pratten, 1990; Kusy,1990).

In Andreasen's study, the differences between frictional force measurements made with saliva as lubricant and those made with a dry wire are insignificant. However, in an other study (Stannard ,1986), artificial saliva was found to increase the coefficients of friction for stainless steel, Beta-titanium and Nickel-titanium compared to dry condition. No change was observed for cobalt-chromium or Teflon. In Pratten's study (1990) artificial saliva increased the frictional force between stainless steel wire, nitinol wire and the stainless stain bracket and the ceramic bracket. In Kusy's finding(1991), the saliva increased the kinetic frictional coeffficient of the stainless steel wire and bracket combination slightly. However, the kinetic frictional coefficient of the beta-titanium wire dropped down to 50% of the values in the dry state and similar to the range of stainless steel. Saliva could be acting to chemically break down the lubricant oxide layer of the stainless steel wire; or acting as an adhesive because of surface tension effects. Therefore, it tends to increase the coefficient of friction of the steel wire in wet state. In the beta-titanium wire, the saliva may function as a lubricant film which minimizes the effect of cold welding between the stainless steel bracket; or the abrasive effect of the ceramic bracket.

RATIONALE

Using a straight wire for initial alignment and leveling the malpositioned teeth seems to be a common procedure in today's orthodontic treatment. Nevertheless, the force system is very complicated and cannot be solved by simple reading of the wire. It is impractical to measure the force inside the mouth directly and solve the problems with static equilibrium because so many variables are involved, such as wire stiffness, wire-attachment geometry, clearance between the bracket and wire, appliance design and friction. Therefore, in most situations, the force system is statistically indeterminate.

Previous experiments reported the quantitative aspects of the force systems by use of the theoretical model. Recently, the analytic model was refined with consideration of the large deflection of the flexible wire and different boundary condition. However, the consideration of the frictional force and the clearance between the wire and attachments was neglected in the study. Also, the data of study only involved the initial force system and only one end of the wire was allowed to slide.

The aim of this study is to build a laboratory model with which the force system can be directly measured. The model will be more similar to clinical situation since clearance between the brackets and wire and the frictional force will be included. By using the electronic devices, moments produced in different class of wire-attachment geometry can be measured under different parameters.

It is hoped that the results of this study will be beneficial to clinical orthodontic treatment thereby allowing the clinicians to predict the exact effect of the wire, which they put into a patient's mouth and thus, minimize the undesirable side effects.

SPECIFIC OBJECTIVES

1. To build a two-bracket experimental model, which can be used to measure the moment generated between the wire and brackets directly.

2. To test the null hypothesis that the moment ratio between two brackets, (M_1/M_2 ratio) in a Class I geometry is independent of the following independent variables a. wire material; b. wire size; c. interbracket width; d. interbracket distance and e. deflection of the wire.

3. To evaluate the relationship between the moment ratio between two brackets and the wire-attachment geometry.

MATERIALS AND METHODS

The Experimental Model

A two-bracket experimental model was developed in the Biomechanics Laboratory of University of Connecticut Health Center. (Fig. 2,3) A bracket was bonded indirectly utilizing a silicon putty type impression material as a carrier to the center of the distal end surface of a stainless steel cylinder shaped beam. The beam was connected to a Transtek angular displacement transducer with a coupling. The transducer was stabilized and connected to the end portion of the apparatus, which could be rotated manually. The moment generated within the bracket would cause rotational displacement of the transducer and changed the voltage output of the device. The electronic signal passed through a signal amplifier and was recorded through the computer, Digital PDP11. The computer was programmed to have the following functions: 1. to check the electronic signal; 2. to calibrate the apparatus and 3. to record the moments generated from the change of voltage outputs of the angular displacement transducers. The counterpart of the model was built in a similar way and was connected to the signal amplifier through a separate channel. The apparatus was adjusted with the brackets lined up in a perfect alignment. One part of the model is built over a horizontal gauge which could be moved horizontally to change the interbracket distance with an accuracy of 0.05mm. The other part could be displaced vertically and the range was recorded by use of a Startlett gauge with an accuracy of 0.005 mm. Before the experimentation, the apparatus was calibrated to determine its accuracy and reliability. (Appendix II)

Procedures

The brackets (wide twin bracket, 0.173" ,Ormco company) were aligned in a straight plane with interbracket distance of 21 mm. The initial interbracket angles were zero in both brackets. The initial moments were recorded with no vertical height difference between two brackets. Then the vertical height were increased from 0 mm to 5 mm in 0.5 mm increment. In each setting, a wire was placed between the brackets and the moments generated were recorded. Ten different straight segments of the same kind of wire were used to obtain thirty readings from each setting. The following wire were tested: 0.016" and 0.018" stainless steel wires (Ormco); 0.016 and 0.018" Beta-titanium wires(Ormco).

The interbracket distance was changed to 7 mm and this time the vertical height increased from 0 mm to 0.5 mm. Readings were taken at 0 mm; 0.1 mm; 0.2 mm; 0.3 mm; 0.35 mm; 0.4 mm; 0.425 mm; 0.45 mm ; 0.465 mm and 0.5 mm. The following wires were used: 0.016" stainless steel wire (Ormco); 0.016" and 0.018" Beta-titanium wire (Ormco); 0.016" and 0.018" Nickel-titanium wire (Ormco). All wire segments except the Nickel-titanium wires were cut from a straight wire. The NiTi wire segments were cut from the distal end portions of the performed shape archwires.

The interbracket distance was then changed to 14mm. Only the 0.016" stainless steel archwire was tested. The moments generated at the following vertical distances between the brackets were recorded: 0mm, 0.5mm, 0.75mm, 1mm, 1.25mm 1.5mm, 1.75mm and 2mm . The reason of increment of vertical distance between two brackets for recording varied among interbracket distances was to ensure that all moments generated from the wires were within its elastic range.

The same procedure were repeated by using medium twin brackets (0.13", Ormco) and single brackets (0.062") at 21mm interbracket distance. Only 0.016" stainless steel wires were used.

In the second part of the experiment, the initial interbracket angles were changed and the vertical distances were also varied. In this combination, different ratios of the interbracket angles could be obtained and the moments generated were recorded. The interbracket distance remained as 21 mm and only the wide twin brackets (0.173") and 0.016" Stainless steel wire were used.

RESULTS

Moments generated between two brackets and wire under different parameters in Class I geometry were recorded and summarized in table 1-4. The relationship between the moment ratio, M_1/M_2, in Class I geometry and different independent variables; interbracket distance, wire size, wire material, bracket width and deflection of the wire was estimated by use of the multiple linear regression statistical method (Appendix III). It was found that the whole model of the independent variables was very weakly related to the dependent variable (M_1/M_2) p value = 0.013. We could not reject the null hypothesis that the moment ratio in Class I geometry has no relationship between the interbracket distance, wire size, wire material, bracket width and deflection at $\alpha = 0.01$ level of significance. However, by further analysis with the single partial F- test, it was found that deflection of the wire was the only significant independent variable accounted for the relationship with the moment ratio.

As the moment ratio, M_1/M_2 in Class I geometry is equal to one, only the moment values obtained from the left bracket and the wire were used for plots shown in (Fig. 4- Fig. 7). As expected, no moment was generated at the beginning of the experiment. When the vertical displacement between two brackets increased to a given amount , the wire began to deflect and engaged the bracket to generate moment. Lack of a moment below this threshold deflection was produced by clearance between brackets and wire. It was clearly showed in the figures that different amounts of clearance existed between the bracket and wire under the different conditions.(Table 5) The flexural stiffness of the wire can be defined as the moment change per unit change of vertical displacement (deflection). In small deflection theory, wire stiffness can be represent by the equation: $P/\Delta = K\ EI/L^3$; Δ=displacement, P=moment, K = a constant, E= Young's modulus and L= length of the wire. After deleting the initial influence of the clearance, the stiffness of a wire could be represented by the slope of the line in the graph. (Table 6) Only the stiffness of stainless Steel and beta-titanium wires were estimated. The deflection of the nickel titanium wire is in linear because of its superelasticity property and therefore the stiffness is not represented by the slope of the line. The theoretical relative stiffness ratio between two wires of different material was calculated and compared to our experimental findings. (Table 7)

As the moments generated between the wire and brackets in Class I geometry were in same direction, two vertical force of same magnitudes in opposite direction should be found in two brackets site to keep the force system in equilibrium. (Fig. 8) The couple produced by the vertical forces was equal to the force magnitude times the perpendicular distance between them. Since horizontal forces were not measured, these values were subjected to considerable error because of the existence of frictional force. The force values were calculated in given vertical displacement between two brackets after deleting the clearance effect. (Table 8)

In the second part of the experiment, the angle between two brackets and the 0.016" Stainless steel wire were changed by varying the original angle setting and the vertical distance between two brackets. The moments generated between brackets and the wire were recorded and summarized. (Table 9) The data was plotted in a scatter diagram with moment ratio, M1/M2 as the y axis and the angle ratio, $\Theta 1/\Theta 2$ (wire-attachment geometry) as the x axis. A best line to represent the relationship between the two variables was drawn.(Fig. 9) The moment ratio at different wire-attachment geometry was estimated by use of this best fitting line. In geometry I ($\Theta 1/\Theta 2$= 1.0), the moment ratio was equal to 1. In geometry II ($\Theta 1/\Theta 2$= 0.5), the moment ratio was equal to 0.87. In geometry III ($\Theta 1/\Theta 2$= 0), the moment ratio was equal to 0.53. In geometry IV ($\Theta 1/\Theta 2$= -0.5), the moment ratio was equal to 0. In geometry V ($\Theta 1/\Theta 2$= -0.75), the moment ratio was equal to -0.37. In geometry VI ($\Theta 1/\Theta 2$= -1.0), the moment ratio was equal to -0.8. The results were compared with the theoretical calculation using small deflection and large deflection beam theory. (Fig. 10 and Table 10)

DISCUSSION

When two brackets have a step relation, a Class I geometry, (vertical discrepancy in the experiment), a straight archwire placed between them will generate two equal moments in the same direction after full engagement. This finding is similar to the previous studies using beam theory (Burstone,1974; Koenig,1989). The moment ratio is independent of interbracket distance, bracket width, wire material and size. However, the moment ratio,M1/M2 was found to be related to the deflection of wire during the initial activation. The influence of the wire deflection was most likely contributing of the clearance between the wire and brackets before it was fully engaged. As the wire was allowed to slide freely in our experimental condition, the frictional force was the only force governed in this initial stage. The frictional force was influenced by the local condition and may account for the minute variation in two bracket-wire sites. In previous studies, the moment ratios between the wire and attachment were calculated after the wire was fully engaged and so the values may not hold true because of the problem of clearance. Another reason to explain the large variation of the moment ratio during this initial activation may be due to the sensitivity of the apparatus and relative percentage experimental error in measuring small moment value.

The clearance between the wire and brackets before fully engaged depends on the size of the wire, interbracket distance and bracket width. For example, a 0.016" Stainless steel wire (wide twin bracket) has a 0.3 mm and 1 mm clearance at 7 mm and 21 mm interbracket distance respectively. The 0.016" wire (single bracket) will have a 2 mm clearance at 21 mm interbracket distance. A 0.018" wire (wide twin bracket) is fully engaged when two brackets have 0.2 mm and 0.5 mm steps at 7 mm and 21 mm interbracket distances respectively regardless the wire material. Clinically, this implies that wider bracket width, larger wire size and smaller interbracket distance will have less clearance between wire and brackets and therefore will allow less tipping of teeth in a mesio-distal direction.

Creekmore (1976) reported that interbracket distance was important to the wire stiffness. He assumed that the wire stiffness is inversely proportional to the cube of the length (interbracket distance). The interbracket distance between the proximal of brackets was significantly changed by the bracket width. A single bracket when placed in the center of the teeth decreased the wire stiffness compared to twin bracket because it increased the interbracket distance. In our study, the relative wire stiffness ratio of a 0.016" Stainless steel wire between a single bracket (0.062" in width) and wide twin bracket (0.17" in width) at a 21 mm interbracket distance (measured between the bracket centers) is 0.62. This approximates the theoretical ratio, 0.63 calculated by measuring the distance between the inner edge of the brackets. This distance represents the actual length of wire and the stiffness of wire is inversely proportional to cube of the length. This finding also indicated that if the wire was allowed to slide freely in both ends, the experimental result showed no difference as compared with the estimation using small deflection theory. Based on the above the stiffness ratio between a single bracket and a wide twin bracket with 7 mm interbracket distance measuring from the center of the teeth would be 0.11. This magnitude of change in wire stiffness is a significant factor in choosing the type of attachment in clinical treatment.

The stiffness of the wire is dependent on the material property and the cross sectional configuration (moment of inertia). In order to have better force control, a clinician may select a wire of large dimension to fill a bracket but made of less stiff material. This idea was proposed by Burstone in 1981. The relative stiffness ratio between two archwires with different materials is proportional to its Young's modulus. In our study, using nominal cross section of the wires, the relative ratio was close to the theoretical ratio if we choose Young's modulus of elasticity of Stainless steel as 25×10^6 p.s.i. (Yoshikawa , 1981) .

The moment ratio generated between two brackets and a 0.016" Stainless steel archwire was found strongly related to the angles of two brackets related to the archwire. The result obtained was fairly close to the finding of the previous studies using beam theory calculation. The experimental moment ratio obtained at different geometries is more similar to the simulation under small deflection model or the large deflection model free to slide at one side. The similarity may be explained by the experimental boundary condition. The wire was free to slide between the brackets without any restriction and no ligation force was used in the experiment. The effect of clearance and friction of wire between brackets seemed not to have a great influence of the moment ratio under this condition. The largest deviation from experimental result was the data obtained from the range when at least one of the moment value was close to zero. The inaccuracy is because of the sensitivity of the apparatus and the exaggerated effect of the arithmetic calculation of ratio. Further, the measuring error of the angulation between the bracket and the wire may also contribute to this difference. The large change of moment ratio ($M1/M2 = -0.37$ to -0.8) with relatively small angle differences (where $\Theta1/\Theta2=$

-0.75 to -1) should be of great concern in everyday clinical orthodontic practice.

Future studies of the angle ratio (Θ_A/Θ_B) relationship to the force system will require a different apparatus which can measure the minute rotational change of the bracket angle. To include micro-strain gauges in the apparatus for measuring forces will add greater accuracy in continuation of the experiment. Additional gauges to measure the horizontal force will show the effects of frictional force. The current apparatus is capable of measuring the moment ratio under other parameters such as different bracket materials, or under varying boundary conditions such as changing ligation forces and other restrictions of the wire to slide.

SUMMARY AND CONCLUSION

The apparatus built in our laboratory demonstrated its capability of measuring and recording the moment generated between the wire and brackets. The reliability and reproducibility of the measurements were tested. Moments generated between the wire and two brackets in Class I wire-attachment geometry were measured under the boundary with no restriction of the wire to slide and no ligation force applied. By plotting the moment change against the unit change of the deflection, the stiffness of stainless steel and beta-titanium wire were obtained by measuring the slope of lines. Relative wire stiffness values were calculated and the result was close to the theoretical value based on linear beam theory; wire stiffness, $\Delta/P=K\ L^3/EI$ (Δ is the displacement; P is the moment; L is the length of the wire; E is the elasticity modulus and I is the moment of inertia of the wire).

The null hypothesis that moment ratio M_1/M_2 generated in Class I geometry is not dependent on the wire size, wire material, interbracket distance, bracket width and wire deflection cannot be rejected. Since the deflection of wire was found to have influence on the moment ratio before the wire was fully engaged because of the clearance between wire and the brackets. The amount of clearance was dependent on the wire size, interbracket distance and bracket type.

Moment ratio, M_1/M_2 was found to be highly related to the wire-attachment geometry. The moment ratios obtained in different classes of geometry were as following: 1.0 in Class I ; 0.87 in Class II; 0.53 in Class III; 0.0

in Class IV ; -0.8 in Class VI geometry. The results were similar to the values obtained from small deflection beam theory or from large deflection beam theory with freedom of the wire to slide. Large variation was found in Class V and Class VI geometries because the moment ratio changed abruptly in this region for small angular differences.

The apparatus was not designed to accurately establish different angle ratios and hence in geometries other than Class I , inaccurate determination of the Θ_1/Θ_2 was responsible for much of the variation. The result obtained in the small moment range has more variation because of the inherent experimental errors such as differences in batch materials and different environment conditions affecting the electronic digital signal of the output.

Further studies with an apparatus can measure the vertical and horizontal force along with the moments will give us a deeper understanding of the force system between the wire and the bracket.

FORCE SYSTEM FROM STRAIGHT ARCHWIRES

IN VARYING TWO BRACKET-GEOMETRIES----AN EXPERIMENTAL STUDY

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APPENDIX I : TABLES AND FIGURES

Table 1 Moments generated between wire and wide twin brackets, Class I geometry - 21mm interbracket distance. n=30 in each cell

Wire type	Displacement mm	Moment1 gm-mm	Moment2 gm-mm
Stainless steel 0.016"	0.0	-1.49± 4.72	-1.84± 1.96
	0.5	-0.35± 4.43	-2.19± 2.00
	1.0	32.96± 21.09	49.27± 21.60
	1.5	253.79± 22.21	266.62± 21.01
	2.0	469.59± 22.31	474.04± 23.57
	2.5	681.66± 18.47	679.17± 21.60
	3.0	877.41± 22.00	868.59± 24.30
	3.5	1060.85± 23.06	1050.06± 22.99
	4.0	1225.41± 32.52	1212.47± 27.39
	4.5	1369.41± 39.98	1357.66± 34.02
	5.0	1529.99± 41.47	1508.24± 39.76
Stainless steel 0.018"	0.0	-0.22± 5.31	-3.33± 3.36
	0.5	-0.42± 5.22	-2.495± 2.02
	1.0	180.98± 10.10	210.15± 8.29
	1.5	506.03± 15.76	507.78± 16.66
	2.0	823.53± 14.73	799.91± 15.31
	2.5	1129.72± 13.49	1084.16± 17.95
	3.0	1404.64± 21.16	1340.49± 21.94
	3.5	1669.81± 23.61	1591.10± 22.25
	4.0	1917.25± 29.02	1805.47± 25.57
	4.5	2145.16± 44.85	2009.21± 32.14
	5.0	2330.49± 56.62	2185.51± 43.02
Beta-titanium 0.016"	0.0	-1.35± 5.85	-2.754± 2.66
	0.5	1.39± 5.41	-1.68± 2.24
	1.0	19.78± 7.28	26.61± 7.43
	1.5	115.41± 9.22	118.35± 10.74
	2.0	207.98± 11.79	207.81± 12.87
	2.5	304.42± 10.75	297.84± 11.51
	3.0	392.28± 13.25	390.05± 14.51
	3.5	486.28± 19.06	475.76± 19.77
	4.0	569.18± 21.39	557.32± 18.37
	4.5	655.99± 22.15	637.75± 18.63
	5.0	733.47± 26.22	713.70± 23.34
Beta-titanium 0.018"	0.0	-0.59± 6.59	-0.93± 2.30
	0.5	-0.44± 6.13	1.74± 5.30
	1.0	82.15± 14.55	97.75± 7.77
	1.5	209.55± 13.92	224.00± 9.23
	2.0	339.30± 12.45	345.30± 11.55
	2.5	461.54± 13.17	467.71± 12.91
	3.0	591.05± 11.57	587.11± 16.21
	3.5	704.83± 17.31	695.62± 18.55
	4.0	824.46± 23.09	804.60± 20.45
	4.5	925.95± 19.86	908.18± 23.49
	5.0	1031.23± 29.71	1007.23± 35.44

Table 2 Moments generated between wire and wide twin brackets, Class I geometry - 7 mm interbracket distance. n=30 at each cell

Wire type	Displacement mm	Moment1 gm-mm	Moment2 gm-mm
Stainless steel 0.016"	0.0	-0.76± 5.48	-3.76± 3.40
	0.1	-0.39± 5.68	-3.36± 1.94
	0.2	0.06± 5.50	-3.71± 2.10
	0.3	31.69± 12.97	70.75± 26.31
	0.35	353.47± 25.44	426.71± 25.87
	0.4	830.02± 28.11	867.65± 27.65
	0.425	1063.40± 31.69	1082.68± 33.31
	0.45	1317.57± 34.05	1317.13± 36.91
	0.475	1548.13± 24.59	1531.79± 31.72
Beta-titanium 0.016"	0.0	0.80± 4.78	-1.69± 2.62
	0.1	2.04± 6.87	-0.50± 2.31
	0.2	0.58± 5.78	-0.83± 2.28
	0.3	5.08± 10.19	12.34± 16.45
	0.35	102.41± 22.01	125.37± 24.24
	0.4	244.43± 24.96	259.58± 30.99
	0.425	324.06± 35.98	335.09± 34.54
	0.45	402.27± 34.66	411.50± 36.81
	0.475	479.65± 45.12	481.44± 44.22
	0.5	567.95± 39.02	565.19± 40.48
Beta-titanium 0.018"	0.0	1.39± 5.53	-3.07± 2.73
	0.1	0.28± 4.73	-2.25± 2.29
	0.2	5.41± 7.06	9.66± 14.44
	0.3	388.67± 39.95	440.68± 37.76
	0.35	638.92± 42.33	682.48± 44.60
	0.4	946.49± 52.39	983.11± 56.90
	0.425	1118.40± 45.94	1150.62± 49.82
	0.45	1253.31± 52.64	1272.91± 58.12
	0.475	1386.84± 59.51	1418.82± 62.43
Nickel titanium 0.016"	0.0	-2.80± 5.71	-0.21± 2.52
	0.1	-3.02± 5.18	-0.63± 3.08
	0.2	-3.01± 4.83	0.25± 3.10
	0.3	14.24± 5.65	39.86± 6.70
	0.35	135.99± 10.16	161.25± 10.97
	0.4	272.54± 15.83	282.35± 18.49
	0.425	336.39± 22.17	337.23± 24.12
	0.45	391.75± 28.13	385.47± 27.33
	0.475	438.58± 28.76	428.70± 30.52
	0.5	495.00± 25.31	481.21± 25.23
Nickel titanium 0.018"	0.0	-1.02± 5.99	-4.29± 2.70
	0.1	-0.48± 4.04	-3.47± 2.75
	0.2	-0.23± 3.35	-1.45± 3.29
	0.3	231.22± 22.50	252.40± 16.54
	0.35	396.13± 15.37	403.33± 18.13
	0.4	528.17± 25.97	533.17± 26.32
	0.425	586.67± 30.55	593.04± 28.45
	0.45	657.99± 30.46	660.47± 29.28
	0.475	715.23± 31.39	718.29± 32.90
	0.5	780.22± 26.68	788.21± 28.10

Table 3 Moments generated between 0.016" stainless steel wire and wide twin brackets, Class I geometry, at 7mm, 14mm and 21mm interbracket distances. n=30 in each cell

Interbracket Distance mm	Displacement mm	$Moment_1$ gm-mm	$Moment_2$ gm-mm
21	0.0	-1.49± 4.72	-1.84± 1.96
	0.5	-0.35± 4.43	-2.19± 2.00
	1.0	32.96± 21.09	49.27± 21.60
	1.5	253.79± 22.21	266.62± 21.01
	2.0	469.59± 22.31	474.04± 23.57
	2.5	681.66± 18.47	679.17± 21.60
	3.0	877.41± 22.00	868.59± 24.30
	3.5	1060.85± 23.06	1050.06± 22.99
	4.0	1225.41± 32.52	1212.47± 27.39
	4.5	1369.41± 39.98	1357.66± 34.02
	5.0	1529.99± 41.47	1508.24± 39.76
14	0.0	-3.01± 4.60	-2.42± 2.93
	0.5	-5.49± 2.95	-1.02± 3.32
	0.75	164.38± 13.52	201.71± 16.30
	1.0	442.56± 42.56	461.07± 39.63
	1.25	715.22± 13.33	738.81± 21.42
	1.5	974.23± 60.16	981.53± 57.00
	1.75	1223.05± 13.33	1273.37± 15.81
	2.0	1475.91± 85.79	1474.84± 74.31
7	0.0	-0.76± 5.48	-3.76± 3.40
	0.1	-0.39± 5.68	-3.36± 1.94
	0.2	0.06± 5.50	-3.71± 2.10
	0.3	31.69± 12.97	70.75± 26.31
	0.35	353.47± 25.44	426.71± 25.87
	0.4	830.02± 28.11	867.65± 27.65
	0.425	1063.40± 31.69	1082.68± 33.31
	0.45	1317.57± 34.05	1317.13± 36.91
	0.475	1548.13± 24.59	1531.79± 31.72

Table 4 Moments generated between 0.016" stainless steel wire and brackets with different width- 0.173", 0.130" and 0.062", Class I geometry, at 21 mm interbracket distance. n= 30 in each cell

Bracket Type	Displacement mm	$Moment_1$ gm-mm	$Moment_2$ gm-mm
Wide twin bracket 0.173"	0.0	-1.49± 4.72	-1.84± 1.96
	0.5	-0.35± 4.43	-2.19± 2.00
	1.0	32.96± 21.09	49.27± 21.60
	1.5	253.79± 22.21	266.62± 21.01
	2.0	469.59± 22.31	474.04± 23.57
	2.5	681.66± 18.47	679.17± 21.60
	3.0	877.41± 22.00	868.59± 24.30
	3.5	1060.85± 23.06	1050.06± 22.99
	4.0	1225.41± 32.52	1212.47± 27.39
	4.5	1369.41± 39.98	1357.66± 34.02
	5.0	1529.99± 41.47	1508.24± 39.76
Medium twin bracket 0.130"	0.0	-1.59± 5.67	-3.16± 3.30
	0.5	-0.43± 4.16	-2.57± 3.86
	1.0	0.22± 6.02	12.27± 12.02
	1.5	157.30± 17.16	194.29± 20.78
	2.0	369.49± 20.88	380.72± 20.29
	2.5	569.47± 21.54	560.57± 22.68
	3.0	729.96± 24.98	731.44± 24.70
	3.5	880.42± 22.65	899.74± 20.13
	4.0	1017.34± 19.81	1050.05± 20.34
	4.5	1153.82± 18.83	1193.42± 19.13
	5.0	1271.47± 17.39	1371.94± 23.06
Single bracket 0.062"	0.0	-1.71± 5.12	-4.26± 2.67
	1.0	-0.48± 6.83	-1.53± 3.45
	2.0	-0.89± 4.18	-2.36± 3.08
	3.0	185.13± 18.45	174.55± 24.12
	3.5	315.41± 20.78	321.36± 20.32
	4.0	446.11± 16.32	465.25± 22.22
	4.5	566.73± 15.93	598.03± 17.73
	5.0	678.38± 15.28	724.06± 20.83
	5.5	782.77± 18.37	842.49± 21.75
	6.0	885.40± 16.56	955.44± 19.68
	6.5	962.88± 21.35	1052.35± 17.78

Table 5 Clearance between wire and bracket under different parameters

Wire Size	Interbracket Distance mm	Bracket Type	Clearance mm
0.016"	21	Wide twin	1
	7	Wide twin	0.3
	21	Single	2
0.018"	21	Wide twin	0.5
	7	Wide twin	0.2

Table 6 Stiffness of wires under different parameters.

Wire type	Interbracket distance mm	Stiffness gm-mm/mm	Bracket type
Stainless Steel 0.016"	7	9583.5	Wide twin
	14	1029.8	Wide twin
	21	363.03	Wide twin
		297.3	Medium twin
		224.19	Single
Stainless Steel 0.018"	21	523.98	Wide twin
Beta-titanium 0.016"	7	3097.5	Wide twin
	21	177.49	
Beta-titanium 0.018"	7	5827.1	Wide twin
	21	235.42	

Table 7 Comparison of theoretical relative stiffness ratio to the experimental ratio with 0.016" stainless steel wire as standard at 21 mm interbracket distance. E= Modulus of Elasticity, d= diameter of round wire.

	Modulus of Elasticity 10^6 psi	Relative Stiffness $E \times d^4$	Experimental relative stiffness
Stainless Steel	25.0	1	1
.016"			
.018"		1.6	1.4
Beta-titanium			
.016"	10.0	0.42	0.49
.018"		0.67	0.65

Table 8 Moment and vertical force generated between a 0.016" stainless steel wire and wide twin bracket at 7 mm and 21 mm interbracket distance, Class I geometry, after eliminating the clearance effect.

Interbracket distance mm	Displacement mm	Vertical force gm	Moment gm-mm
21	0.5	20	212
	1.0	40	421
	1.5	58	613
	2.0	76	796
	2.5	91	959
	3.0	105	1104
	3.5	120	1259
7	0.05	131	459
	0.075	195	683
	0.1	265	927
	0.125	329	1150

Table 9 Moment ratio in different wire-attachment geometries. M1/M2= moment ratio; Θ1/Θ2 determines the wire-attachment geometry.

ANGLE 1	ANGLE 2	MOMENT 1	MOMENT 2	Θ1/Θ2	M1/M2
5.44	15.62	-1615.15	-1356.19	0.35	1.19
4.90	15.08	-1564.18	-1277.88	0.32	1.22
4.36	14.54	-1444.49	-1216.70	0.30	1.19
3.81	13.99	-1309.18	-1143.59	0.27	1.14
3.27	13.45	-1196.86	-1061.92	0.24	1.13
2.73	12.91	-990.18	-994.66	0.21	1.00
2.18	12.36	-946.88	-913.68	0.18	1.04
1.64	11.82	-789.32	-865.67	0.14	0.91
1.09	11.27	-602.34	-783.98	0.10	0.77
0.55	10.73	-496.42	-721.68	0.05	0.69
0.00	10.18	-351.14	-643.36	0.00	0.55
-0.55	9.63	-232.18	-572.87	-0.06	0.41
-1.09	9.09	-146.60	-494.72	-0.12	0.30
-1.64	8.55	-94.06	-438.75	-0.19	0.21
-2.18	8	-54.48	-389.98	-0.27	0.14
-2.73	7.45	-21.63	-346.41	-0.37	0.06
-3.27	6.91	12.40	-284.43	-0.47	-0.04
-3.81	6.37	29.29	-260.50	-0.60	-0.11
-4.36	5.82	23.73	-236.56	-0.75	-0.10
-4.90	5.28	16.35	-212.68	-0.93	-0.08
-5.44	4.74	97.75	-142.11	-0.87	-1.45
-5.98	4.2	169.21	-82.76	-0.70	-0.49
-6.52	3.66	234.63	-19.84	-0.56	-0.08
-7.06	3.12	279.29	-24.40	-0.44	-0.09
-7.59	2.59	308.01	-19.12	-0.34	-0.06
-8.13	2.05	362.38	-20.75	-0.25	-0.06
-8.66	1.52	414.70	38.88	-0.18	-0.09
-9.20	0.98	464.52	40.40	-0.11	-0.09
-9.73	0.48	503.70	44.13	-0.05	-0.09
-10.26	-0.08	551.30	100.13	0.00	0.18
-10.78	-0.60	657.02	173.82	0.06	0.26
-11.31	-1.13	755.69	290.24	0.10	0.38
-11.83	-1.65	826.27	378.89	0.14	0.46
-12.36	-2.18	915.08	474.07	0.18	0.52
-12.88	-2.70	1006.18	551.74	0.21	0.55
-13.39	-3.21	1109.84	624.11	0.24	0.56
4.56	-25.44	-719.32	-1797.08	-0.18	0.40
5.10	-24.90	-646.05	-1767.60	-0.20	0.37
5.64	-24.36	-471.10	-1414.24	-0.23	0.33
6.19	-23.81	-473.02	-1582.75	-0.26	0.30
6.73	-23.27	-390.00	-1534.50	-0.29	0.25
7.27	-22.73	-318.71	-1463.79	-0.32	0.22
7.82	-22.18	-240.81	-1376.28	-0.35	0.17
8.36	-21.64	-154.23	-1285.01	-0.39	0.12
8.91	-21.09	-147.13	-1256.54	-0.42	0.12
9.45	-20.55	-144.55	-1216.35	-0.46	0.12
10.00	-20.00	-91.54	-1151.09	-0.50	0.08
10.55	-19.45	-33.35	-1091.81	-0.54	0.03
11.09	-18.91	35.60	-998.29	-0.59	-0.04
11.64	-18.36	49.91	-963.23	-0.63	-0.05
12.18	-17.82	54.25	-949.32	-0.68	-0.06
12.73	-17.27	45.38	-902.16	-0.74	-0.05
13.27	-16.73	86.38	-859.70	-0.79	-0.10
13.81	-16.19	143.17	-767.60	-0.85	-0.19
14.36	-15.64	228.74	-626.38	-0.92	-0.37
14.90	-15.10	324.27	-599.13	-0.99	-0.54
14.56	-32.21	-209.17	-1662.18	-0.45	0.13
15.10	-31.57	-165.02	-1575.57	-0.48	0.10
15.64	-31.03	-0.81	-1513.93	-0.50	0.00
16.19	-30.48	-18.38	-1465.61	-0.53	0.01
16.73	-29.94	15.56	-1478.14	-0.56	-0.01
17.27	-29.40	80.11	-1392.12	-0.59	-0.06
17.82	-28.85	36.52	-1355.19	-0.62	-0.03
18.36	-28.31	97.62	-1374.53	-0.65	-0.07

18.91	-27.76	92.48	-1354.22	-0.68	-0.07
19.45	-27.22	163.17	-1304.25	-0.71	-0.13
20.00	-26.67	211.169	-1246.00	-0.75	-0.17
20.55	-26.12	334.45	-1177.98	-0.79	-0.28
21.09	-25.58	394.86	-1081.17	-0.82	-0.37
21.64	-25.03	525.17	-1037.06	-0.86	-0.51
22.18	-24.49	586.902	-1039.05	-0.91	-0.56
22.73	-23.94	706.58	-993.27	-0.95	-0.71
23.27	-23.40	766.52	-854.73	-0.99	-0.90
23.82	-22.85	805.64	-827.24	-0.96	-1.03
24.37	-22.30	896.58	-765.20	-0.92	-0.85
24.91	-21.76	990.76	-611.43	-0.88	-0.62
25.46	-21.21	1066.86	-496.15	-0.83	-0.47
26.00	-20.67	1095.04	-445.83	-0.79	-0.41
26.55	-20.12	1139.50	-454.27	-0.76	-0.40
27.10	-19.57	1157.14	-481.40	-0.72	-0.42
27.64	-19.03	1183.38	-390.09	-0.69	-0.33
28.19	-18.48	1241.86	-334.67	-0.65	-0.27
28.73	-17.94	1296.40	-274.14	-0.63	-0.21
29.28	-17.39	1358.63	-174.73	-0.60	-0.13
29.83	-16.84	1379.01	-130.16	-0.56	-0.09
30.37	-16.30	1399.39	-119.94	-0.54	-0.09
30.92	-15.75	1403.33	-122.42	-0.51	-0.09
31.46	-15.21	1459.28	-110.75	-0.48	-0.08
32.01	-14.66	1446.42	-96.44	-0.46	-0.07
32.56	-14.11	1483.47	-89.21	-0.43	-0.06
33.10	-13.57	1520.94	-51.18	-0.41	-0.03
33.65	-13.02	1587.63	-10.39	-0.39	0.00
10.44	15.44	-1547.76	-1650.00	0.68	0.94
9.89	14.89	-1500.04	-1607.81	0.66	0.93
9.39	14.35	-1432.97	-1545.06	0.65	0.93
8.8	13.80	-1363.48	-1483.11	0.64	0.92
8.26	13.26	-1354.23	-1365.75	0.62	0.99
7.71	12.71	-1276.85	-1365.75	0.61	0.93
7.16	12.16	-1209.01	-1289.4	0.59	0.94
6.62	11.62	-1157.55	-1255.43	0.57	0.92
6.07	11.07	-1062.07	-1155.55	0.55	0.92
5.53	10.53	-1008.54	-1115.51	0.53	0.90
5.00	10.00	-957.40	-1068.27	0.50	0.90
4.46	9.46	-884.241	-996.62	0.47	0.89
3.91	8.91	-822.11	-925.00	0.44	0.89
3.36	8.36	-754.69	-869.87	0.40	0.87
2.52	7.52	-656.99	-777.54	0.34	0.84
1.97	6.97	-563.58	-712.45	0.28	0.79
1.42	6.42	-525.93	-631.81	0.22	0.83
0.88	5.88	-456.05	-559.87	0.15	0.81
0.33	5.33	-374.80	-502.74	0.06	0.75
-0.21	4.79	-293.65	-414.84	-0.04	0.71
-0.76	4.24	-182.50	-332.73	-0.18	0.55
-1.30	3.70	-104.05	-263.20	-0.35	0.40
-1.85	3.15	-26.34	-186.55	-0.59	0.14
12.94	15.44	-1506.11	-1713.15	0.84	0.88
12.40	14.90	-1487.82	-1654.40	0.83	0.90
11.85	14.35	-1424.57	-1602.08	0.83	0.89
11.30	13.80	-1416.28	-1569.07	0.82	0.90
10.75	13.25	-1392.11	-1556.43	0.81	0.89
10.20	12.70	-1327.74	-1475.05	0.80	0.90
9.65	12.15	-1287.89	-1442.11	0.79	0.89
9.10	11.60	-1217.26	-1375.49	0.78	0.88
8.55	11.05	-1147.57	-1283.23	0.77	0.89
8.00	10.50	-1107.04	-1235.42	0.76	0.90
7.50	10.00	-1066.59	-1192.14	0.75	0.89
6.95	9.45	-1011.12	-1129.97	0.74	0.89
6.40	8.90	-938.14	-1064.61	0.72	0.88
5.85	8.35	-870.65	-980.11	0.70	0.89
5.30	7.80	-809.722	-919.98	0.68	0.88
4.75	7.25	-760.32	-850.29	0.66	0.89
4.20	6.70	-691.69	-775.40	0.63	0.89
3.65	6.15	-625.95	-697.06	0.59	0.90
3.10	5.60	-538.92	-621.35	0.55	0.87
2.55	5.05	-502.87	-548.01	0.50	0.92
2.00	4.50	-428.61	-473.22	0.44	0.91

1.45	3.95	-365.90	-401.91	0.37	0.91
0.90	3.40	-296.04	-321.17	0.26	0.92
0.35	2.85	-220.73	-258.06	0.12	0.86
-0.2	2.3	-166.52	-186.72	-0.09	0.89
-0.75	1.75	-65.29	-115.18	-0.43	0.57

Table 10 Force Systems From a Straight wire

Class of Bracket Geometry	Method	M1/M2
I	LFr	1.0
I	NLFr	1.0
I	NLFi	1.0
I	Exp	1.0
II	LFr	0.8
II	NLFr	0.8
II	NLFi	0.75
II	Exp	0.87
III	LFr	0.5
III	NLFr	0.5
III	NLFi	0.4
III	Exp	0.53
IV	LFr	0.0
IV	NLFr	0.0
IV	NLFi	0.2
IV	Exp	0.0
VI	LFr	-1.0
VI	NLFr	-1.1
VI	NLFi	-1.0
VI	Exp	-0.8

Wire used = 0.016" Stainless Steel wire

L= Linear (small deflection)
NL= Nonlinear (large deflection)
Fr= Free to slide at right bracket
Fi= Fixed

Exp= Experimental

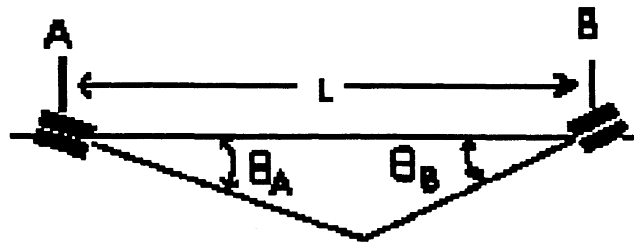

Fig. 1 Wire -attachment geometry is defined by the interbracket axis (L) and the angles of the brackets at positions A and B (Θ_A and Θ_B).

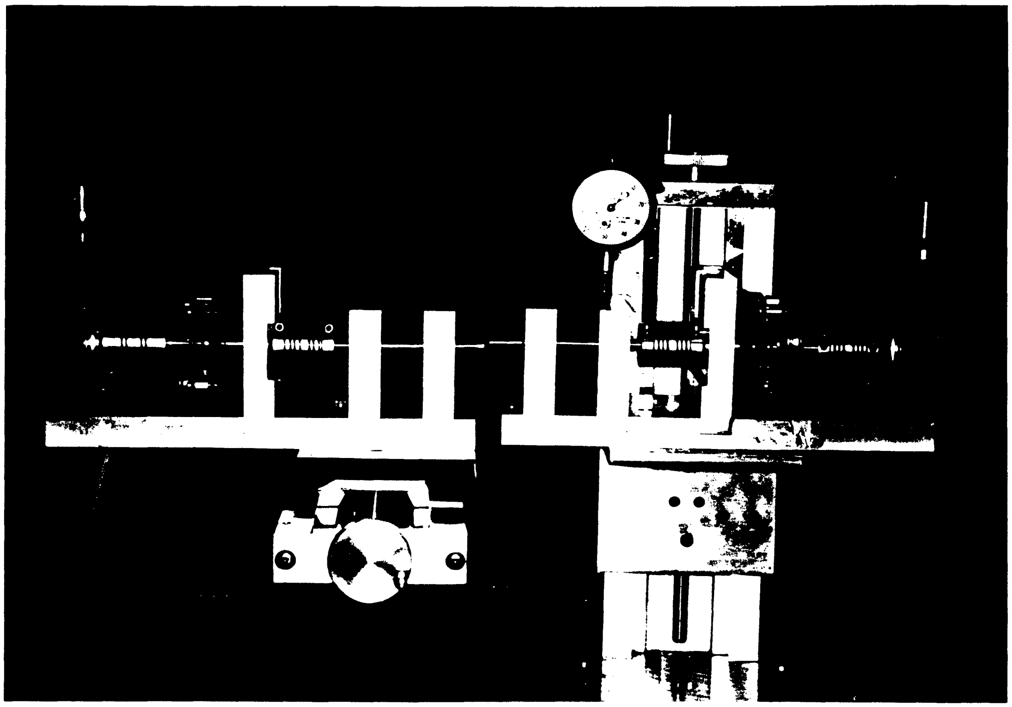

Fig. 2 Apparatus setup

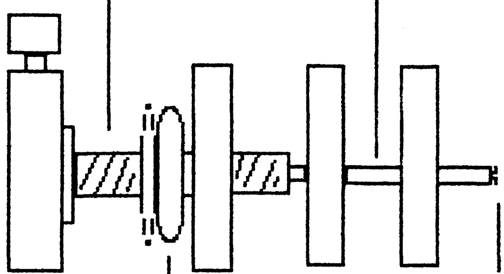

Fig.3 Diagram showing detail parts of the instrument

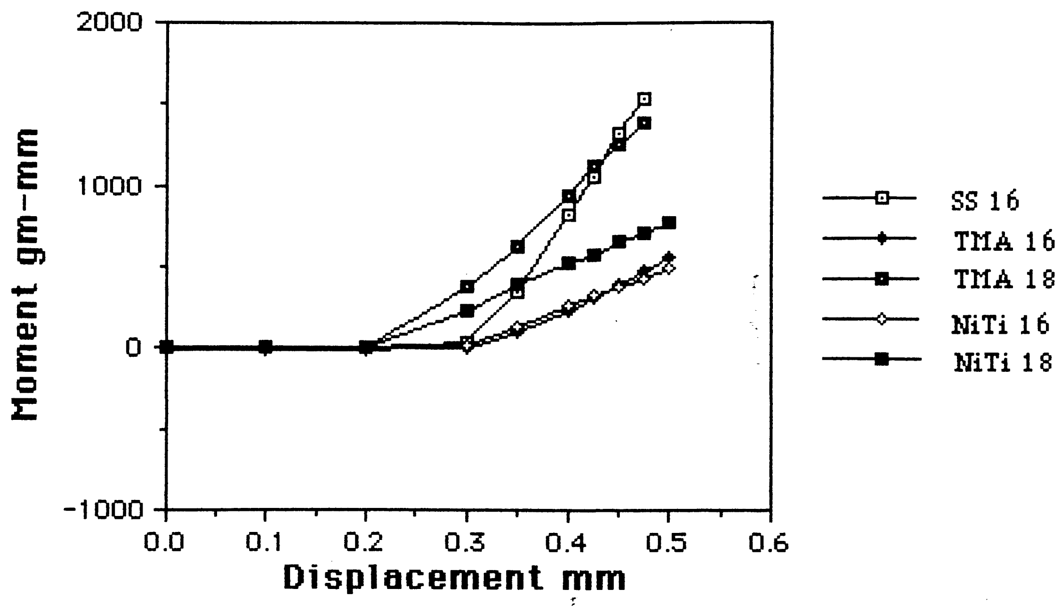

Fig. 4 Moment- displacement for Class I geometry, wide twin bracket, 7mm interbracket distance. Wire cross section x .001"

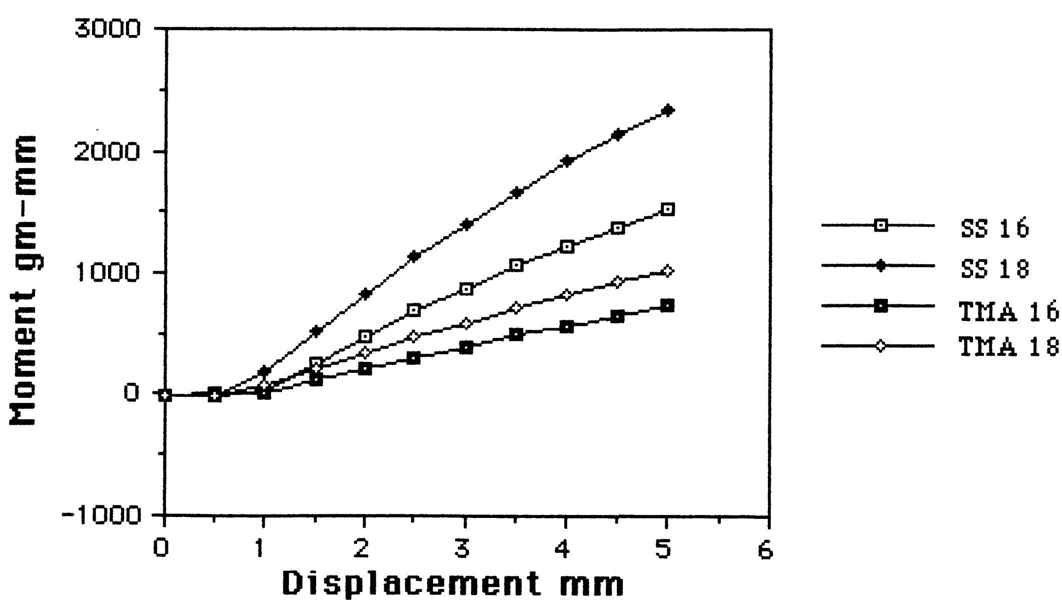

Fig. 5 Moment-displacement for Class I geometry, wide twin bracket, 21 mm interbracket distance. Wire cross section x 0.001"

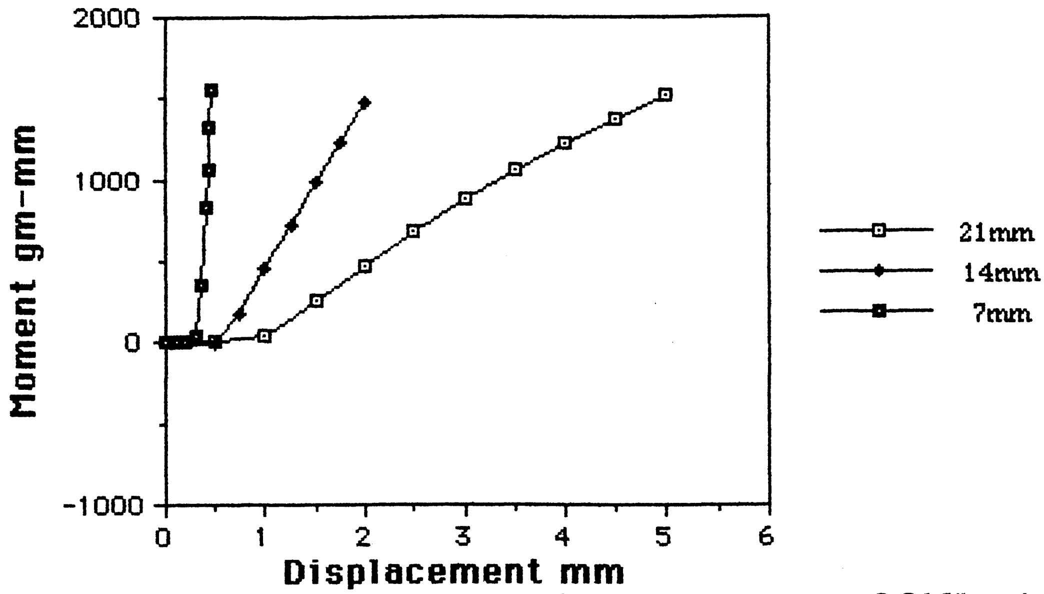

Fig. 6 Moment -displacement for Class I geometry, 0.016" stainless steel wire, wide twin bracket at 21 mm, 14 mm and 7 mm interbracket distance.

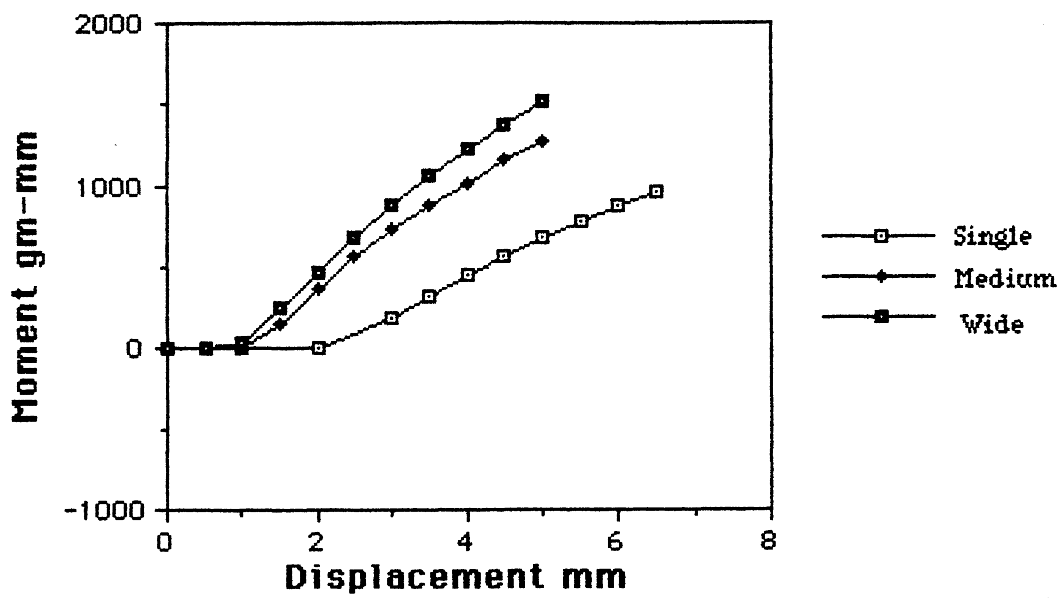

Fig.7 Moment -displacement for Class I geometry, 0.016" stainless steel wire, 21 mm interbracket distance, single, medium and wide twin bracket.

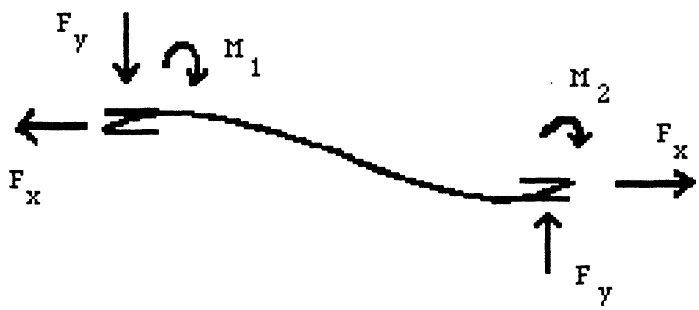

Fig. 8 Force System acting on the attachment in Class I Wire-attachment geometry, M= moment , F_y= vertical force, F_x= horizontal force.

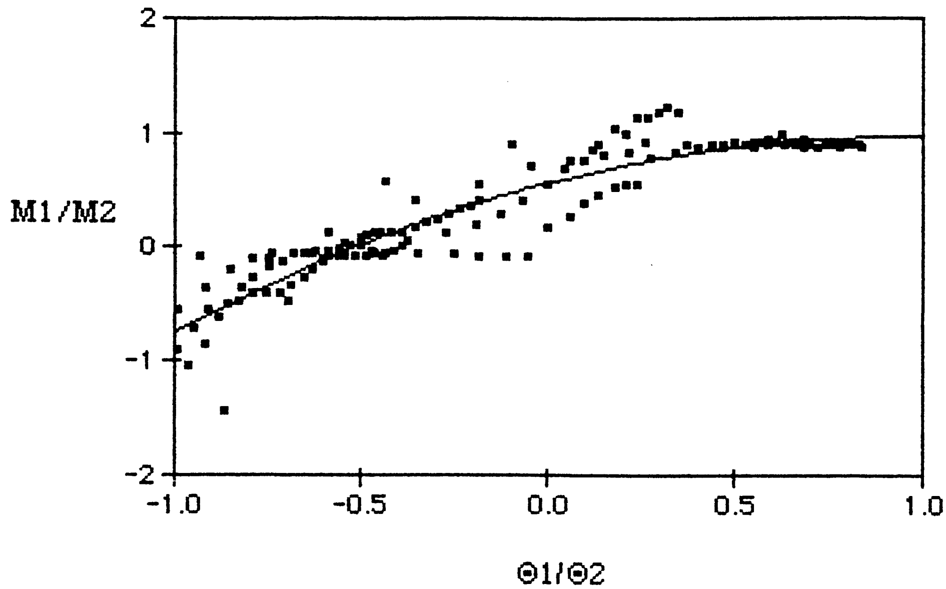

Fig. 9 Scatter diagram with best fitted line to show the relation between Θ1/Θ2 (Class geometry) and M1/M2 (Moment ratio).

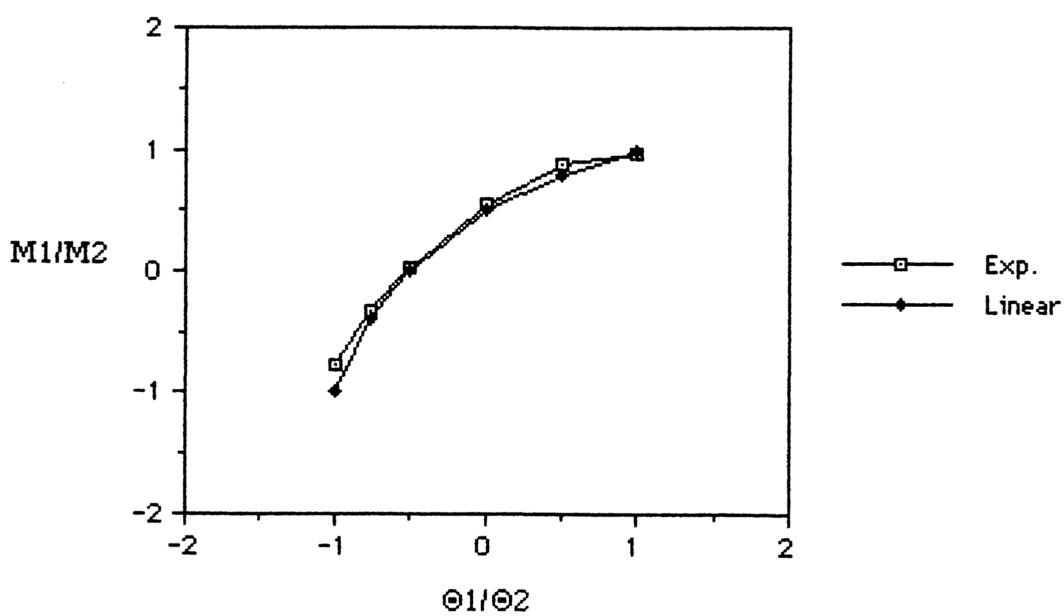

Fig. 10 Graphic presentations of moment ratio (M1/M2) changes with the wire-attachment geometry (Θ1/Θ2) in the experiment (Exp.) and in linear beam theory (Linear).

APPENDIX II : CALIBRATION

The apparatus was calibrated by using different scale of weights which generated moments through a fixed length of 0.021" x 0.025" Stainless steel wire. The wire was fully engaged into the bracket without ligation and the distance between the vertical force application and the center of the bracket was kept constant. The moment generated was equal to the force times distance. The calculated value is used to calibrate the apparatus and test its reproducibilty. (Fig. 11 and 12)

Linear regression statistical method was used to estimate the relationship between the vertical force and the moment generated. The ANOVA tables (Table 11 and Table 12) showed perfect relation between the two variables and demonstrated the reproducibility of the apparatus.

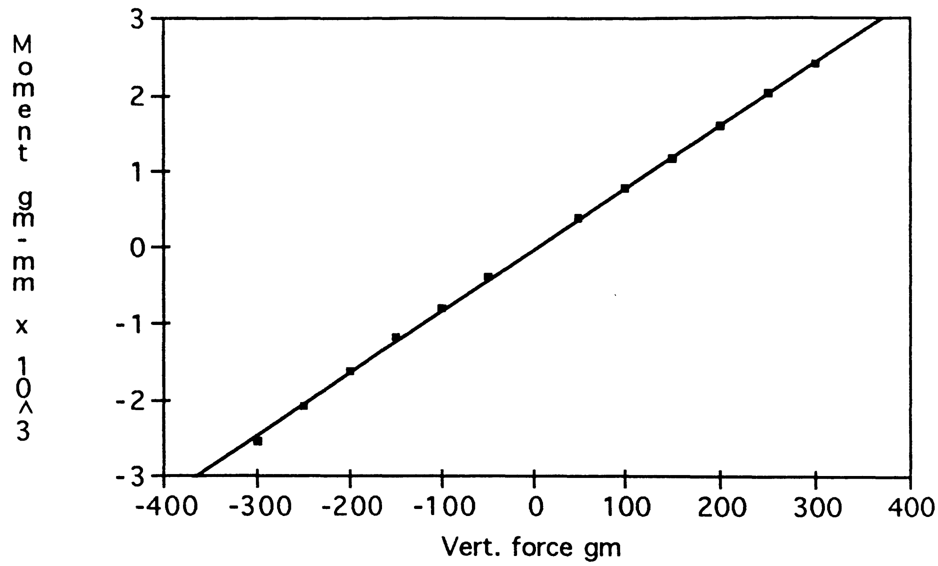

Fig. 11 Best-fitting straight line to vertical force-moment data of calibration of the left angular displacement transducer.

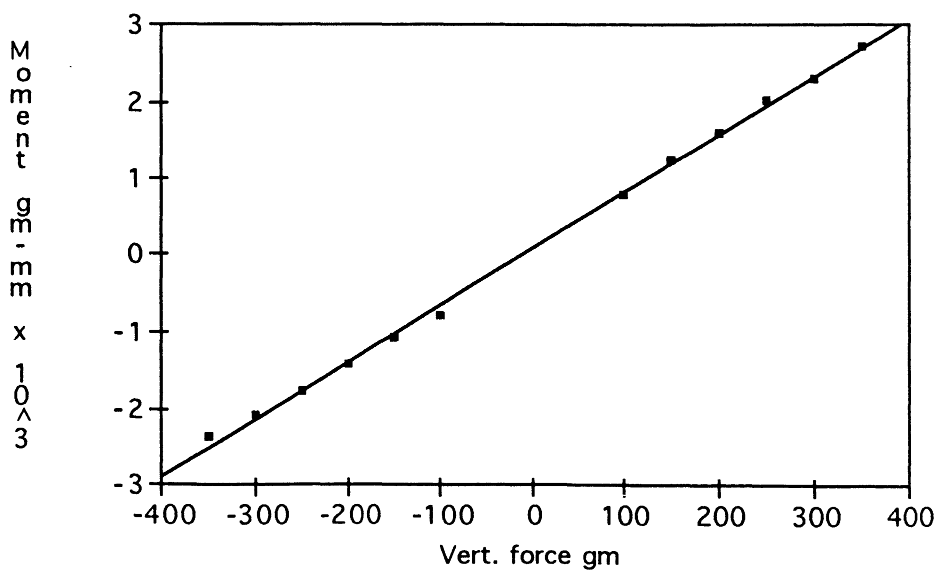

Fig. 12 Best-fitting straight line to vertical force-moment data of calibration of the right angular displacement transducer

Table 11 ANOVA table to show the linear regression test of moment and the vertical force in left bracket

Data File: Calib-18

Source	Sum of Squares	Deg. of Freedom	Mean Squares	F-Ratio	Prob>F
Model	30118251.6	1	30118251.6	21048.7	0.000
Error	14308.8	10	1430.9		
Total	30132560.4	11			

Coefficient of Determination (R^2)	1.0
Adjusted Coefficient (R^2)	1.0
Coefficient of Correlation (R)	1.0
Standard Error of Estimate	37.8
Durbin-Watson Statistic	0.7

Table 12 ANOVA table to show the linear regression test of moment and the vertical force in right bracket.

Data File: Calib-19

Source	Sum of Squares	Deg. of Freedom	Mean Squares	F-Ratio	Prob>F
Model	38263604.4	1	38263604.4	7831.2	0.000
Error	48860.6	10	4886.1		
Total	38312465.0	11			

Coefficient of Determination (R^2)	1.0
Adjusted Coefficient (R^2)	1.0
Coefficient of Correlation (R)	1.0
Standard Error of Estimate	69.9
Durbin-Watson Statistic	1.3

APPENDIX III : DATA ANALYSIS

Response: ln(M1/M2)

Summary of Fit

Rsquare	0.14262
Root Mean Square Error	0.789826
Mean of Response	-0.22374
Observations (or Sum Wgts)	110

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.1989859	1.45656	0.82	0.4123
Deflection	0.2327171	0.0678	3.43	0.0009
Size	-118.6988	87.3831	-1.36	0.1773
Inter	-0.019092	0.01854	-1.03	0.3056
Width	4.6814332	2.7986	1.67	0.0974
SS	-0.497281	0.27437	-1.81	0.0728
TMA	-0.235895	0.25257	-0.93	0.3525

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
Deflection	1	1	7.3501066	11.7823	0.0009
Size	1	1	1.1510679	1.8452	0.1773
Inter	1	1	0.6613784	1.0602	0.3056
Width	1	1	1.7455831	2.7982	0.0974
SS	1	1	2.0492579	3.2850	0.0728
TMA	1	1	0.5441904	0.8723	0.3525

Whole-Model Test

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	10.688266	1.78138	2.8556
Error	103	64.254017	0.62383	Prob>F
C Total	109	74.942282		0.0130

Response: ln(M1/M2)

Summary of Fit

Rsquare	0.044543
Root Mean Square Error	0.82976
Mean of Response	-0.22374
Observations (or Sum Wgts)	110

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.3755785	1.52925	0.90	0.3705
Size	-111.3236	91.7734	-1.21	0.2279
Inter	0.0202346	0.01532	1.32	0.1893
Width	1.8229869	2.80691	0.65	0.5175
SS	-0.519815	0.28816	-1.80	0.0741
TMA	-0.233004	0.26533	-0.88	0.3819

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
Size	1	1	1.0130844	1.4714	0.2279
Inter	1	1	1.2017410	1.7454	0.1893
Width	1	1	0.2904112	0.4218	0.5175
SS	1	1	2.2404687	3.2541	0.0741
TMA	1	1	0.5309420	0.7712	0.3819

Whole-Model Test

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	3.338159	0.667632	0.9697
Error	104	71.604123	0.688501	Prob>F
C Total	109	74.942282		0.4399

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